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NAVORD REPORT 4189

A METHOD FOR PREDICTING IGNITION ENERGY REQUIREMENTS OF PRACTICAL PROPELLANT SYSTEMS. PART I

20 DECEMBER 1955

U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

NAVORD Report 4189

A METHOD FOR PREDICTING IGNITION ENERGY REQUIREMENTS

OF PRACTICAL PROPELLANT SYSTEMS. PART I.

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ABSTRACT: This report covers initial results of an attempt to provide a scientific basis for determining ignition energy requirements of practical gun and rocket systems. As the first phase of this work, an analysis was made of 29 rounds for guns ranging from 20 mm to 15 inch. From this study an important fact has emerged: the dominant factor in determining ignition energy requirements in guns is the product of the area of the propellant system (including other areas exposed to ignition products) and the experimental ignition energy per unit area of the propellant. Future work is expected to establish the relative importance of secondary factors and to refine the equation for quantitatively designing gun ignition systems.

U. S. NAVAL ORDNANCE LABORATORY
White Oak, Maryland

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This report correlates ignition system requirements for 29 gun rounds of various calibers. Except for the 3 inch gun all rounds have been service accepted and presumably the ignition systems have been optimized empirically. The results, while not final, should provide some guidance to those designing ignition systems for guns. This work was performed under Task NOL-B2d-02-1-55.

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By direction

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ILLUSTRATIONS

NOMENCLATURE

A Total surface area exposed to ignition gases, cm^2

D Diameter of propellant charge, cm

H_e Heat of explosion, cal./g

L Length of propellant charge, cm

Q Total energy in ignition system, cal.

q_c Experimental energy required per unit area of propellant for ignition in three milliseconds, cal./cm^2

q_g Ratio of energy in ignition system to surface area exposed to ignition gases (Q/A), cal./cm^2

A METHOD FOR PREDICTING IGNITION ENERGY REQUIREMENTS OF PRACTICAL PROPELLANT SYSTEMS. PART I.

I. INTRODUCTION

Up to the present time, the determination of ignition energy requirements for guns and rockets has been a process which combined art and experience with trial and error. The present work has yielded a rough basis for the scientific prediction of such requirements and with further development it is expected that a more precise equation will be provided.

This work was the outgrowth of a previous investigation in which ignition energies were determined for a series of propellants. These were determined in a locked-stroke compressor and under pressures and temperatures sufficient to bring about ignition in three milliseconds. Ignition intervals in guns and some rockets are comparable to this value. This data and a theoretical treatment, which permits extension of the data to other ignition intervals and ambient temperatures of the propellant, have been reported (1). A logical application of this data was the determination of whether the product of the area of a propellant and its ignition energy requirements per unit area was the dominant factor in determining ignition energy requirements for practical systems.

The viewpoint that an ideal ignition system would simultaneously ignite all surfaces of the propellant has been widely accepted. It would seem logical that the above-mentioned product would thus be at least a major factor in determining practical ignition energy requirements. Lack of experimental data on the amounts of energy required to ignite unit areas of propellant or the feeling that the summation of other factors was more important may have discouraged investigation of this factor. Whatever the cause, there is only a little data reported which indicates much interest in this factor. An experimental study on rockets by Warren and Cronhardt (2) is probably the most closely related work.

The investigation of this product has been fruitful and the first phase of the work is described below.

II. APPROACH TO THE PROBLEM

It was decided that a comparison of the amounts of energy present in practical ignition systems (3) with the theoretical quantities indicated by the area - ignition energy product would be a good starting point. A few rough calculations have been made on rockets and these will be extended. Principal emphasis has so far been on guns and it is this data which is described here.

From the beginning, it was recognized that there were many complications which might make evaluation difficult. The rate at which a primer supplies energy, the ambient temperature of the propellant, the position and design of the ignition system, the length/diameter ratio of the propellant charge, the porosity of the propellant bed, the extent to which one part of the propellant ignites another, the quantity and location of free volume, and other factors would probably have some influence on a system's ignition energy requirements. If, in spite of the many uncertainties involved, a good correlation of Q with the product of the total surface area (A) and the ignition energy per unit area (q_c) for the propellant were obtained, then this product could be considered dominant.

III. SOURCES OF DATA

The rounds so far analyzed have been largely selected because the necessary data on them were readily available. It is surprisingly difficult to obtain complete-round, detailed data on American guns. Complete-round data from intelligence reports by Picatinny Arsenal on captured ammunition have been particularly useful as well as some older British manuals. Although we presently have unanalyzed data on many additional guns and are acquiring more, the present data only include a number of different rounds from test firings on the 3"/70 American gun and data from 18 different, service-accepted rounds, including British 10" and 15" guns and captured guns of 20 mm, 37 mm, 47 mm (l and s), 50 mm (l and s), 88 mm (l and s), and 152 mm calibers, where l and s mean long and short charge. Black powder and smokeless powders were used as ignition materials in the primers, and a variety of primer locations and designs is included. A number of propellant compositions, grain geometries, and packings are represented, including the short, multiperforate, random-packed type and types in which long bundles of unperforated (cylindrical and strip) or single-perforated rods were used.

The sources of information which form the basis for analysis of the rounds considered in this report are listed in Table I. In general, the primary data for a given round falls into four categories: it is descriptive of the ignition-energy source, of the propellant, of the powder chamber and of the degree of ignition achieved. In the following sections, each of these areas of information is treated individually.

IV. PROCESSING OF APPLICABLE DATA

A. Ignition Energy Data

Data in this class consists of composition and weight of each component which supplies energy for the ignition of the propellant. Heat of explosion is generally not given, and must be found elsewhere.

Information is often incomplete concerning the initiator material in which, by electrical or mechanical means, burning is started. Where its weight is unknown, its energy contribution must be neglected. Where weight is given, but data on heat of explosion is unobtainable, the corresponding value for black powder is arbitrarily assigned. The errors thus incurred are small, for the energy derived from this unit usually amounts to considerably less than 1% of the total ignition energy supplied.

Although black powder of the usual military composition (74% potassium nitrate, 16% charcoal, 10% sulfur) plays a contributing role in most ignition systems, there seems to be no general agreement on a "best" value for its heat of explosion. For the purpose of this work, an average value is used which is based on all available figures, as shown in Table II. Each figure is weighted according to the number of powder granulations which it represents. In cases where a range is given, its mid-point is adopted as a mean figure. Water present in the reaction products is assumed gaseous.

The resulting average value of 698.8 cal./g is used throughout this work. No claim is made as to its accuracy; it is regarded simply as the most reasonable present estimate. If future investigation shows it to be substantially in error, corrections may very readily be applied to the calculated data in which it appears.

Ignition energy for the 37 mm, 50 mm and 88 mm rounds treated in this report is chiefly supplied by a charge of smokeless powder. Since chemical composition is given for all such powders, heat of explosion can be calculated. It is assumed equal to the "calorimetric value" computed from the figures used by Pike (29), thus taking into account the thermal contribution or demand of each ingredient of the powder. Heats of explosion obtained in this manner range from 690 to 991 cal./g. Where these powders are contained in bags made from nitrocellulose, the same method is used for computing energy supplied by the bag material.

Nitrocellulose, the chief ingredient in these energy sources, is present in varying degrees of nitration; its energy content varies accordingly. The following expression, taken from Reference 29, relates this factor to calorimetric value for nitrocellulose:

$$\text{Cal. Val.} = 140p - 810$$

where Cal. Val. = calorimetric value at constant volume, cal./g
p = weight percent nitrogen in nitrocellulose.

This equation is based upon a critical survey of the literature, and is believed to represent the best information presently available. It is used in this work wherever heat of explosion for nitrocellulose is needed.

B. Propellant Data

Primary data on the propellant include chemical composition, geometry and dimensions of the individual grain, dimensions of the overall charge, and charge weight. These permit the calculation of surface area, solid volume, and ratio of length to diameter for the entire propellant charge. Other useful figures are sometimes given, such as grain density and number of grains per unit weight. Exact computation of the latter is possible if dimensions and density of the grain are known.

In the absence of experimental data, density is estimated from chemical composition. This procedure requires knowledge of the densities of the various constituents of the propellant, for it involves calculating the volume occupied by each constituent in its pure state and adding together these figures; its accuracy depends upon the assumption that the volume of the blend is equal to the sum of the volumes of the individual constituents. For seven rounds in this report where sufficient information is available, check calculations show that the average error in density due to the use of this approximation is 4.2%.

Density for nitrocellulose, often the major propellant ingredient, is taken as 1.66 g/cc., regardless of degree of nitration. Apparently, as stated in Reference 30, increased nitration produces no marked change in density, since the enlarged volume tends to be offset by greater molecular weight. Several sets of data relating specific gravity to percent nitrogen are given by Fabel (31) but these show no general agreement.

Nominal grain diameter for the Cordite propellant used in the 10" and 15" rounds is described in the British source (21) as the diameter of the die through which the cylindrical grain is extruded. Actual service diameter is less than this, due to solvent loss during drying, and is calculated from the following equation:

$$D_d = D_e(V_d/V_e)^{1/3}$$

where V_e = volume of a given length of extruded grain, before drying

V_d = volume of same grain, after drying

D_e = diameter of grain, before drying (nominal diameter)

D_d = diameter of grain, after drying (service diameter)

V_d is found from values for service density of different types of Cordite (32). V_e is then computed from percentage-composition data before and after drying (21) by adding to V_d the volume of solvent lost during the drying process. The service diameter of Cordite Mk. I is thus found to be 91.7% of the nominal diameter stated in Reference 21; for Cordite M.D., the corresponding figure is 85.5%.

Three types of surface go to make up the total surface area to which energy is transferred by the ignition gases. These are (1) the propellant surface, which constitutes on the average 90% of the total surface area; (2) the metal surfaces within the powder chamber, including the chamber walls, the primer body and the projectile base; and (3) the bags of rayon or silk cloth which are often used to encase the ignition charge or the propellant. In contrast to cloth made from nitrocellulose, these fabrics contribute no energy to the ignition process, and are regarded simply as inert surfaces. No attempt is made to calculate precisely their effective area. Instead, they are assumed to consist of sheet material rather than woven cloth, and surface area is computed from length and diameter on this basis, taking into account both sides of the sheet. In comparison to the propellant, the bags contribute very little to total surface area, and the error introduced by this assumption can thus be neglected. It was shown in Reference 1 that under short transfer times from a hot gas to a solid the thermal properties of the solid had little effect on the amount of energy transferred. This provides some justification for lumping all areas together.

C. Powder Chamber Data

For the calculation of the powder-chamber areas mentioned above, it is necessary to know the internal configuration and dimensions of the chamber. This information is most often supplied by a sectional drawing which is dimensioned or drawn to scale. Such a drawing also makes possible the estimation of total volume available within the chamber. Free volume is then computed as the difference between available volume and solid volume of the propellant charge.

D. Degree of Ignition

Except for the 3"/70 data, which represent a development program carried out at the Naval Proving Ground, all rounds treated in this report are service-accepted. Although it is not known what acceptance criteria were applied, ignition is assumed to be satisfactory.

For the various 3" rounds shown in Table II, degree of ignition achieved is indicated by the tabulation of percent hangfires. In Table III and Figure 1, only those 3" rounds are represented which show no hangfires under any of the conditions tested.

V. RESULTS AND DISCUSSION

The results of some of the calculations are listed in Table III. Note the large ranges of primer energies and propellant areas included. Q/A is called q_g. Experimental values of q_c were taken directly or estimated from compressor data. The quantity q_g/q_c, which is equal to Q/Aq_c is thus a valuable comparison basis.

The first rounds investigated were for the 3"/70 gun, using Naval Proving Ground data from test firings made as part of an ignition and ballistics study. Tests in the first report on these firings (15) were all made with the same type primer but with propellant grains of various sizes and therefore different areas. Compressor tests also indicated that there was some variation in ignition energy requirements among the propellants used, due to small differences in chemical composition. The test rounds were fired at temperatures ranging from -35°F to 120°F. Analysis has begun on some data on firings included in a more recent Naval Proving Ground report (16) in which tests using modified primers were included. The results of the calculations on the first group of firings and some data from the more recent group are included in

Table IV. As ignition energy requirements increase with decreasing temperature, the temperatures at which hangfires occur are good indications of the adequacy of ignition. There is a good correlation between the values of q_g/q_c and the temperatures at which hangfires occur. If the absence of hangfires at -35°F is used as the criterion of successful ignition, then only those rounds in which q_g/q_c was .82 or greater were satisfactory. Two rounds with higher values were not satisfactory by this criterion, though marginal (RNP-295-S with 372 grain primer and q_g/q_c = .90 and HKPC-1 with 504 grain primer and q_g/q_c = 1.07). The highest value tabulated was 1.63 for RNP-377-S propellant and the 604 grain primer. Although excessive pressures were not encountered with this combination at 120°F, pressure steps were worse with this primer than with the 404 grain primer. The 604 grain primers had additional vent holes. This effectively allowed the primers to supply energy at a higher overall rate but without a corresponding increase in the localized evolution rate at each vent. The importance of this modification was demonstrated by the excessive pressures developed when a primer from which the extra vents were omitted was inadvertently used. It thus seems that a value of q_g/q_c as low as .82 and as high as 1.63 can give ignition of a fairly satisfactory nature, but in some instances limits should be narrower.

The average value of q_g/q_c for the twelve types of rounds in Table III is 2.88. This average includes errors due to the use of a constant q_c for each propellant and due to the assumption that all the energy in the primer was transferred to the propellant (without regard to the design of the primer or the difficulties imposed by the propellant bed on the distribution of energy). Adjustment in q_c for various ambient propellant temperatures and for various energy transfer rates can be made when these temperatures and rates are known. The above value of q_g/q_c would thus be reduced by a factor of about 1.4 if computations were based on the larger values of q_c at ambient temperatures of -35°F rather than 77°F (298°K). The 3 millisecond ignition energy is probably near the lower limit for practical systems. Ignition intervals can be estimated by subtracting the travel time of the projectile from the ejection time. Ejection times measured for the 3"/70 gun were as low as 12 milliseconds at high ambient temperatures of the charge, but were considered normal up to 25 milliseconds (25 - 50 ms is long, greater than 50 is hangfire). The projectile travel time was estimated at 10 milliseconds, assuming an average velocity of one-half the muzzle velocity and a distance of travel equal to the length of the barrel. Normal ignition intervals of 2-15 milliseconds were thus obtained. A 15 millisecond interval of energy transfer would require about 2.5 times as much energy for ignition as a

2 millisecond interval. All parts of the propellant, of course, are not simultaneously ignited and it is also doubtful if there is time for the full contents of the primer to discharge during a 2 millisecond ignition interval. Considering these and other sources of error, the average value of $q_g/q_c = 2.88$ is a good correlation, but a better basis of comparison is given below.

Figure 1 is a log-log plot of A versus $Q(L/D)/q_c$, where L/D is the length/diameter ratio of the propellant charge. A good straight line is obtained; the line drawn being determined by the method of least squares and having a Pearson correlation coefficient of .97. From this line the following equation was obtained:

$$Q = 12.1\, A^{.99}\, q_c\, D/L$$

A good straight line is also obtained if the corrections for L/D and q_c are omitted, but the correlation coefficient is worse. This equation plus the values of q_g/q_c obtained show rather clearly that the product of the propellant's area (plus other exposed area) times its ignition energy requirements per unit area is the dominant factor in determining the amount of ignition energy needed for guns.

The scatter about the line was found not to be a function of A. Ideally, q_g/q_c should be constant; thus we can analyze the scatter by plotting q_g/q_c against any desired variable. This was the basis of the inclusion of the L/D correction. From the data now available there are already indications that other factors causing the scatter can be determined after more data is acquired. It should be pointed out that the use of an exponent of one for D/L is arbitrary. When more data becomes available a different value may be assigned.

If factors which are roughly functions of A (such as charge weight, free chamber volume, and total chamber volume) are used to replace A in the log-log type plots, straight line relationships can be obtained. The scatter is worse, however, and the slopes obtained are distinctly different from one. Only a line with a slope of one on a log-log plot will yield a straight line with linear coordinates. It is thus concluded that A is the important factor and the correlation obtained with the other factors is purely a reflection of the degree of their dependence on A.

In analyzing scatter to obtain additional correction factors for calculating ignition energy requirements, it seems that considerable information will be obtained on the efficiencies of various designs of igniters as well as the effects of factors such as shapes and sizes of propellants. This is an extra dividend beyond original expectations.

VI. CONCLUSIONS

1. The product Aq_c is dominant in determining ignition energy requirements of guns.

2. Statistical treatment of present data indicates that one of the important secondary factors is the ratio L/D. Considerable reduction in scatter is obtained by including this factor.

3. An equation is thus obtained for calculating ignition energy requirements for gun systems -

$$Q = k\ A\ q_c\ f_1\ f_2 \text{---} f_n, \text{ where}$$

the f's are functions of secondary factors; f_1 being a function of L/D and the other f's being functions of variables which future analysis should establish. The constant "k" will vary with the f's if the constant portion of each f is separated from the variable portion.

4. Analysis of these f functions will be useful in assessing the effects of such variables as propellants' shapes, sizes, and packing and the effectiveness of various designs of ignition systems.

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TABLE I

SOURCES OF DATA FOR THE ROUNDS CONSIDERED IN THIS REPORT

Type of Round	Literature Source
20 mm	Reference (3)
"	" (4)
37 mm	" (5)
"	" (6)
"	" (7)
47 mm, Long Charge	" (8)
47 mm, Short Charge	" (9)
50 mm, Long Charge	" (10)
" " "	" (11)
" " "	" (12)
50 mm, Short Charge	" (13)
" " "	" (14)
3 inch	" (15)
"	" (16)
88 mm, Long Charge	" (17)
" " "	" (18)
88 mm, Short Charge	" (19)
152 mm	" (20)
10 inch	" (21)
15 inch	" (21)

TABLE II

HEAT OF EXPLOSION FOR MILITARY BLACK POWDER

Information Source	Powder Granulation	Conditions	H_e Value (cal./g)	Weight Assigned	Contribution to H_e
Ref. (22)	Large Grain	Unknown	725.7	1	725.7
" (22)	Fine Grain	"	738.3	1	738.3
" (23)	FFFG & Meal	Du Pont Bomb; 1 atm. He	705.5 (mean)	2	1411
" (23)	FFFG & Meal	Parr Bomb; 1-15 atm.	700 (mean)	2	1400
" (24)	FFFG	Unknown	702	1	702
" (25)	Unknown	"	694.6	1	694.6
" (26)	RLG	"	718.1	1	718.1
" (27)	A-1, A-3a & FFFG	68 atm. N_2	670 (avg.)	3	2010
" (28)	Unknown	Unknown	685	1	685
			Totals:	13	9084.7

$$\text{Average Value for } H_e = \frac{9084.7}{13} = 698.8 \text{ cal./g}$$

TABLE III

SERVICE-ACCEPTED ROUNDS[7]

Round Description		Charge Weight g	Chg.Lgth. / Chg.Diam.	A, Total Area Exposed to Ignition Gases, cm^2	Q, Total Energy in Ignition System, cal.	$q_g = Q/A$ cal./cm^2	q_c, Exptl. Energy Req'd. per Unit Area, cal/cm^2	q_g/q_c	Notes Applicable
20 mm	Round A	35.5	4.5	1273	757	.594	.264	2.25	1,5,8
	Round B	37.7	4.5	1292	736	.569	.264	2.16	1,5,8
	Average	36.6	4.5	1283	746	.582	.264	2.20	
37 mm	Round A	191	5.34	3701	3367	.910	.281	3.24	1,6,9
	Round B	168	5.21	3564	2740	.769	.281	2.74	1,6,9
	Round C	170	5.08	3326	3409	1.025	.281	3.65	1,6,9
	Average	176	5.21	3530	3172	.901	.281	3.21	
47 mm, Long Charge	Round A	425	8.47	6672	2257	.338	.281	1.20	4,6,8
47 mm, Short Charge	Round A	167	3.74	3440	2300	.669	.264	2.53	4,6,8
50 mm, Long Charge	Round A	692	4.31	12,700	8761	.690	.281	2.46	1,6,9
	Round B	700	5.43	9400	11,990	1.276	.281	4.54	1,6,9
	Round C	880	5.23	11,650	12,380	1.062	.281	3.78	1,6,9
	Average	757	4.99	11,250	11,040	1.009	.281	3.59	
50 mm, Short Charge	Round A	530	3.19	10,240	10,680	1.042	.281	3.71	1,6,9
	Round B	505	3.45	10,340	10,930	1.057	.281	3.76	1,6,9
	Average	518	3.32	10,300	10,800	1.050	.281	3.74	
3 in.[7]	Mean	4545	4.71	56,010	22,870	.424	.349	1.23	2,5,8
88 mm, Long Charge	Round A	5475	7.51	46,460	16,880	.363	.344	1.06	1,5,9
	Round B	5402	7.44	50,500	18,080	.358	.358	1.00	1,6,9
	Average	5439	7.48	48,480	17,480	.360	.351	1.03	
88 mm, Short Charge	Round A	2471	5.20	23,950	17,800	.743	.281	2.65	1,6,9
152 mm	Round A	7824	3.38	60,090	22,940	.382	.264	1.45	2,5,8
10 in.	Round A	36,290	3.12	302,400	318,200	1.052	.264	3.98	3,6,8
15 in.	Round A	194,100	2.17	617,200	1,270,000	2.058	.264	7.80	3,6,8

Notes:
1 Cylindrical grain, 1 perforation.
2 Cylindrical grain, 7 perforations.
3 Cylindrical grain, no perforations.
4 Strip grain, no perforations.
5 Short grains, random-packed.
6 Long grains, tied in bundle.
7 All rounds listed are service-accepted except for the 3-inch. Table IV gives a detailed treatment of rounds fired in the 3-inch development program. "Mean" quantities given in Table II for 3-inch ammunition are averages of values for the two rounds in that program situated at the extremes of the group of rounds in which ignition was considered successful.
8 Principal ingredient in primer: black powder.
9 Principal ingredient in primer: smokeless powder.

TABLE IV

EXPERIMENTAL ROUNDS FOR THE 3"/70 GUN, U. S. NAVY

Propellant[1]	Weight of Black Powder in Primer, grains	Percent Hangfires[2] (No. of rounds fired shown in parentheses) Propellant Temperature: -35°F.	Propellant Temperature: 0°F.	Propellant Temperature: 120°F.	A, Total Area Exposed to Ignition Gases, cm^2	Q, Total Energy in Ignition System, cal.	$q_g = Q/A$ cal./cm^2	q_c, Exptl. Energy Required per Unit Area, cal./cm^2	q_g/q_c
HKPC-2	372	100 (4)	90 (10)	0 (19)	58,910	16,920	.287	.376	.76
EX-7077	372	25 (4)	4 (24)	0 (20)	60,620	16,920	.279	.358	.78
HKPC-1	372	100 (6)	100 (10)	0 (20)	59,920	16,920	.282	.358	.79
EX-7031	372	50 (4)	16 (19)	0 (20)	59,830	16,920	.283	.358	.79
EX-7147	404	0 (3)	— (0)	— (0)	62,700	18,340	.293	.358	.82
RNP-295-S	372	75 (4)	10 (10)	0 (10)	52,790	16,920	.320	.358	.90
RNP-361-S	372	0 (4)	0 (10)	0 (10)	54,500	16,920	.310	.340	.91
RNP-377-S	372	0 (4)	0 (10)	0 (10)	49,320	16,920	.343	.340	1.01
HKPC-1	504	30 (10)	— (0)	0 (10)	59,920	22,370	.332	.358	1.07
HKPC-2	604	0 (15)	— (0)	0 (10)	58,910	27,400	.465	.376	1.24
RNP-377-S	604	— (0)	— (0)	0 (5)	49,320	27,400	.556	.340	1.63

Notes: 1 Each propellant charge consists of short, cylindrical, random-packed grains having 7 perforations.
Charge weight varies from 4440 grams to 4600 grams.
Ratio of charge length to charge diameter varies from 3.99 to 4.92.
2 Round is considered a hangfire when ejection time exceeds 50 milliseconds.

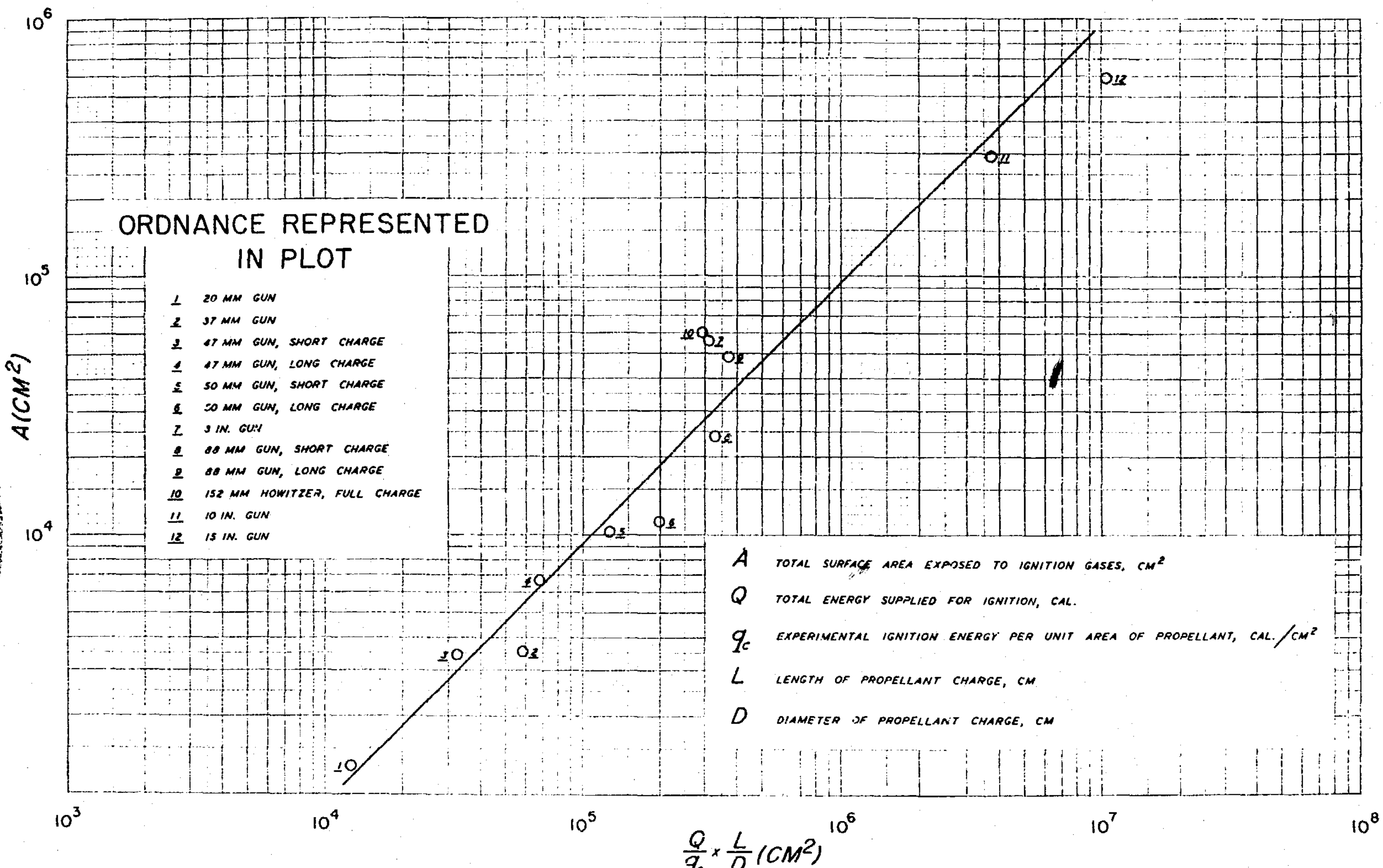

FIG.I ENERGY FUNCTION VS TOTAL SURFACE AREA FOR VARIOUS SERVICE ROUNDS

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